# *The Physical and Chemical Conditions of the Chesapeake Bay*

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## *ABSTRACT*

As assessment of the physical and chemical conditions of the Chesapeake Bay estuarine system indicates: (1) that there are marked natural spatial and temporal variations of temperature, and that man has had a measurable effect, in local areas, on the temperature distribution, but that the present inputs of heated waters from power plants do not pose a threat to the Bay; (2) that there are large natural spatial and temporal variations of salinity, and that man has had almost no effect on the salinity distribution; (3) that man's activities have increased the frequency, duration, and extent of low oxygen zones in the upper reaches of a number of the tributaries; (4) that man's activities have resulted in large inputs of nutrients which have produced undesirable conditions in a number of the tributaries, but that the nutrient levels in the main body of the Bay are at an acceptable level; (5) that the Bay is being rapidly filled with sediments, and that the fine-grained sediments have a number of deleterious indirect effects on the ecology of the Bay; and (6) that there are large natural variations in the distributions of heavy metals, and suggests that levels have probably always been relatively high.

The Chesapeake Bay is an estuary—a semi-enclosed coastal body of water having free access to the ocean and within which seawater is measurably diluted by freshwater from land drainage (Pritchard, 1967). Freshwater from numerous rivers and streams is mixed within the semi-enclosed Chesapeake Bay basin with seawater that enters through the Virginia capes. The mixing, primarily by tides, produces density gradients that drive the characteristic two-layered circulation pattern that eventually leads to the discharge of the freshwater into the Atlantic Ocean. The Chesapeake Bay is actually a complex estuarine *system* comprising the Bay proper and its tributary estuaries.

The Chesapeake Bay estuarine system was formed by the most recent rise in sea level which began approximately 15,000-18,000 years ago. With the retreat of the glaciers at the end of the Wisconsin glaciation, sea level rose rapidly from a position approximately 125 m below its present level. As it rose it advanced across the previously exposed continental shelf, reaching the present mouth of the Chesapeake Bay basin less than 10,000 years ago. The sea penetrated into the Bay basin, drowning the ancestral river valley system which was carved during the previous low stand, transforming the riverine system into an estuarine system.

The Chesapeake Bay is a classic example of a drowned river valley estuary. The age of the *estuary* decreases from mouth to head; the northern Chesapeake Bay is probably no more than 3,000-4,000 years old. The Chesapeake Bay estuary then, is very young geologically. Like other estuaries it is an ephemeral feature on a geologic time scale. It is being rapidly filled with sediments; sedi-

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ments from rivers, from shore erosion, from primary productivity, and from the sea. As the Bay contracts in volume, depth, and eventually in area, the intruding sea will be progressively displaced seaward, transforming the estuary back into a river valley system. Finally, the Susquehanna will reach the sea through a depositional plain and the transformation will be complete. If relative sea level remains nearly constant, this process will take, at most, a few tens of thousands of years to complete. If relative sea level falls, the estuary's lifetime will be shortened. If relative sea level rises, the life of the estuary will be increased.

Man's activities can greatly accelerate the rate of infilling, thus shortening the Bay's geological lifetime. But, more important, the by-products of his activities such as sewage, pesticides, herbicides, heavy metals, and sediment may alter the estuarine system, or segments of it, to the extent that its useful biological and recreational lifetimes will be cut drastically shorter than its geological lifetime—perhaps several orders of magnitude shorter.

The Chesapeake Bay, like other estuaries, is a dynamic environment characterized by marked natural fluctuations of many of its physical and chemical properties. The fluctuations, both short- and long-term, may be produced by processes active within the Bay, or they may be inherited from processes active in the drainage basin, perhaps hundreds of kilometers away. The water that enters the Bay from each of the tributaries carries with it a set of properties produced by that water's history; a history in part natural and in part man-made.

The purposes of this paper are to describe some of the prevailing physical and chemical conditions of the Chesapeake Bay estuarine system and to assess man's impact on these conditions. This requires the establishment of the existing spatial and temporal distributions of several of the important characteristic properties and an evaluation of how these characteristics have been affected by man and his activities. Some of the more important properties are: (1) temperature, (2) salinity, (3) dissolved oxygen, (4) nutrients, (5) sediment, (6) heavy metals, (7) pesticides, (8) herbicides, and (9) oil. Because of limitations of time, space, and data, I will confine my remarks to the first 6 items. The last 3—pesticides, herbicides, and oil—may represent major threats to the Bay, but there are very few data.

### Temperature

Water temperature is important because of its effect on density, on oxygen solubility, and on a number of other important physico-chemical properties of seawater. Temperature is also very important biologically. It is one of the most important factors governing the occurrence and behavior of all forms of life.

During the past 20 years the Chesapeake Bay Institute has determined the distribution of temperature in the main body of the Chesapeake Bay and its major tributaries a relatively large number of times. The results have been presented in a series of graphical summary reports (Whaley and Hopkins, 1952; Stroup and Lynn, 1963; Seitz, 1971).

There are marked natural temporal and spatial variations of water temperature in the Chesapeake Bay estuarine system. Fig. 1 illustrates the spatial variations in surface temperature that can occur along the longitudinal axis of the Bay. These data depict the distribution of surface temperature along the axis of the Bay in August, 1961. The data show a range in surface temperature

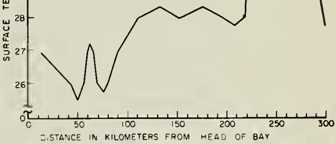


Fig. 1. Longitudinal profile of surface temperature (°C) along axis of Chesapeake Bay during August, 1961.

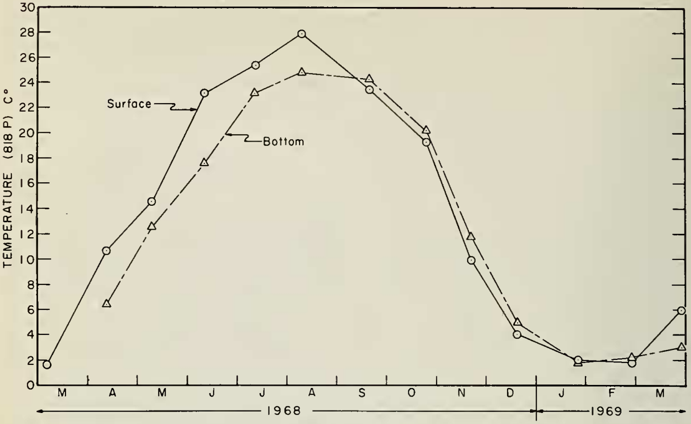


Fig. 2. Monthly variation of temperature (°C) at a station (818P) in the mid-Bay (from Seitz, 1971).

greater than 7°C and local gradients sometimes exceeding 1°C/km. This distribution is somewhat unusual in the magnitude of the variation, but the general features of the spatial variation are representative. More- or -less randomly-spaced variations of 1.5-2.5°C are not unusual. In addition, temperatures in the Virginia portion of the Bay are, on the average, about 0.5°C warmer than those in the Maryland portion.

There are also marked temporal variations in water temperature. The average diurnal variation of water temperature at a depth of about 1.2 m below mean low water (MLW) in the mouth of the Patuxent estuary was 1.2°C during 1947 (Beaven, 1960). The maximum diurnal variation Bevan observed at this depth was 3.0°C, which occurred several times in late winter, spring, and early fall.

The annual range in temperature in the open Bay is from about 0°C to approximately 29°C. Fig. 2 shows the variations of surface and bottom temperature over a 13-month period in 1968-1969 at a 34-m station in the mid-Bay. The surface temperature ranged from about 1.7°C in March to more than 28°C in August. The temperature of the bottom waters showed a similar pattern of seasonal heating and cooling, with only a slightly smaller range.

In addition to the seasonal changes, there are relatively large short- and long-term variations of water temperature. Daily measurements of surface temperature were taken for more than 50 years by the Coast and Geodetic Survey at selected tidal observation stations in some of the tributary estuaries. Similar data are not available for the Bay proper,

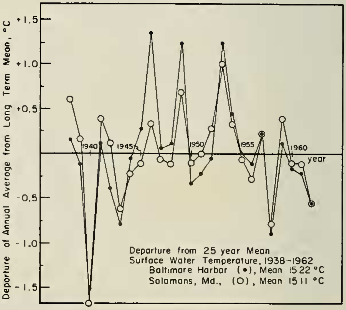


Fig. 3. Departures of mean annual surface temperatures (°C) from 25-year mean surface temperatures at Fort McHenry (Baltimore Harbor) and Solomons, Maryland (Patuxent estuary).

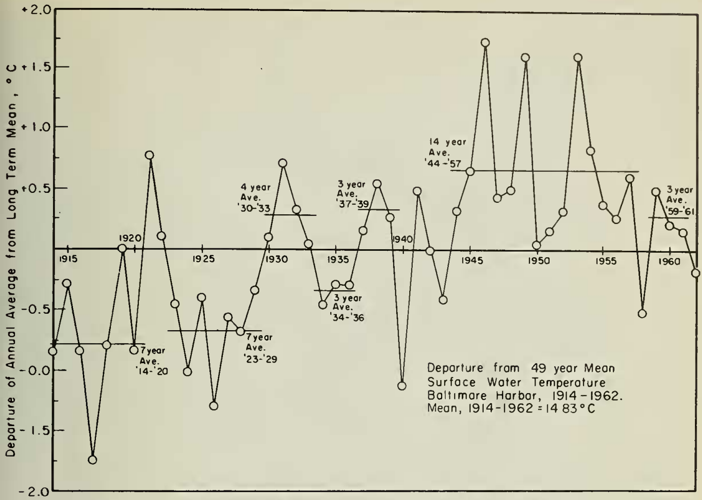


**Fig. 4.** Departures of mean annual surface temperatures (°C) from 49-year (1914-1962) surface temperatures off Fort McHenry. Mean surface temperatures averaged over periods of several years are also shown.

but comparison of the monthly or yearly averages of the data taken at stations in widely separated tributaries indicates that these data are quite representative of large segments of the Bay. This is shown by fig. 3, which summarizes surface-temperature data collected at Fort McHenry in Baltimore Harbor and at Solomons, Maryland on the lower Patuxent estuary more than 100 km away. The *departures* of the average annual temperatures from their long-term 25-year mean temperatures are plotted for each of these stations. The 2 curves track each other very well, indicating that the annual variations in water temperature occur over a large segment of the Bay system and suggesting that these data are representative of conditions in the Bay proper.

An extended temperature record for Fort McHenry is presented in fig. 4, which is a plot of the *departure* of the annual mean surface temperature from the long-term, 49-year mean for the period 1914-1962. The figure shows that the mean annual temperature had a range over the 49-year period of about 3.5°C, and the maximum difference between consecutive years was greater than 1.5°C. The data also show that the mean temperature, averaged over periods of several years, departs significantly from its long-term, 49-year mean. For example, over the 14-year interval from 1944 through 1957, the mean temperature was about 0.7°C higher than the 49-year mean of 14.8°C.

There are then, marked *natural* spatial and temporal variations in water temperature. Superimposed upon these natural fluctuations are the thermal effects of man's activities. Man directly affects the distribution of temperature in segments of the Bay and its tributaries where he utilizes part of the available water as cooling water for the condensers of electric generating plants (fig. 5). It might be useful to look at examples of the magnitude and the areal extent of the temperature increases associated with 2 power plants—one in operation and the other under construction.

The Chalk Point power plant is a fossil fuel plant located on the upper Patuxent

Fig. 5. Map of electric generating plants in Chesapeake Bay region.

estuary. The plant has a design power production of 710 MWE from 2 units. At this loading, the plant rejects heat to the environment at a rate of about $1.2 \times 10^{10}$ cal/sec ($2.8 \times 10^9$ BTU/hr). When operating near full capacity the plant utilizes cooling water at the rate of about 31 $m^3$/sec, or approximately 1/3 of the total available dilution water from the Patuxent. After the cooling water passes through the condensers it flows through a long canal and discharges into the Patuxent approximately 2.4 km upstream from the plant.

The Chesapeake Bay Institute made a detailed study of the temperature and salinity distributions in the vicinity of the plant between 25 September and 5 October 1967 (Carter, 1968). Carter used these data to compute the distribution of excess temperature produced by the plant—the temperature elevation above that which would occur if the plant were not operating. The excess temperature was greater than 1°C over the entire cross-section of the estuary adjacent to the plant, and the sectional mean value of the excess temperature in this segment was about 2°C. The effects on the longitudinal distribution of temperature were also quite pronounced. The mean sectional excess temperature exceeded 0.5°C for a distance of about 18.5 km along the estuary.

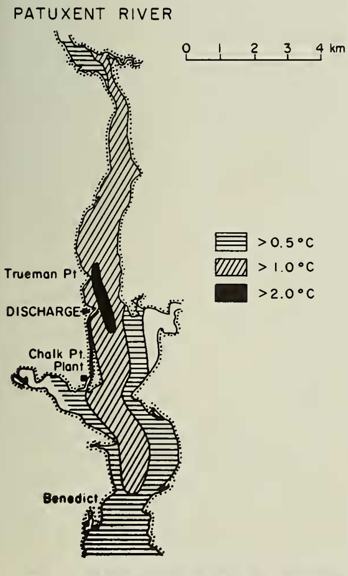


Fig. 6. Horizontal distribution of *excess* temperature *minimum* (°C) of Chalk Point Plant (H.H. Carter, personal communication).

The horizontal distribution of the excess temperature *minimum* is shown in fig. 6. The figure represents the minimum excess temperatures observed during a tidal cycle. Superimposed upon this distribution is a plume of higher excess temperature which oscillates with the tide. The plume is not shown in fig. 6. The maximum excess temperatures in the plume and in the discharge canal reach more than 5°C higher than those shown.

Clearly the Chalk Point power plant has a demonstrable effect on the *temperature distribution* of the Patuxent estuary. The more important question however, is whether the observed temperature increases have a measurable ecological effect on the system. Since the plant has been operating, there have been 2 mass mortalities; one of finfish, including many striped bass, and the other of blue crabs. Both of these kills were confined to the discharge canal. The finfish kill was very probably caused by an overdose of chlorine, and not by thermal effects as originally reported. The cause of the crab kill may have been a combination of high temperature and high levels of chlorine in the canal.

The massive finfish kill occurred some time in the early morning of 27 September 1967. On the evening before the kill, members of the Chesapeake Bay Institute fished in the discharge canal and did not observe any dead fish. The plant operated near full capacity the day of the kill, and throughout the 5-day periods preceding and succeeding the kill. The continuous record of temperature in the canal, near its mouth, shows clearly that on the day of the kill there was not an increase in temperature (fig. 7). In fact, higher temperatures were observed both before and after the massive kill with-

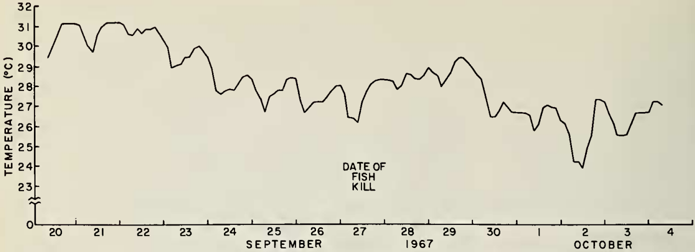


Fig. 7. Temperature record (°C) from Chalk Point Plant discharge canal covering period of massive fish kill on 27 September 1966.

out any apparent harmful effects. Fig. 7 shows no evidence to indicate the possibility of thermal shock, and indicates that a stress other than temperature must be sought to explain the massive mortality of fish.

At the time of the kill a dye tracer, Rhodamine B, was being injected into the plant discharge. It is well known that this dye is not a biocide and would not have caused the kill. The dye however, gives a clue to the probable cause of the kill. At the time of the kill there was a sharp loss of dye within the canal; a loss which could not be explained by physical processes. Since it was known that chlorine destroys the dye, the plant's chlorination log was inspected and it was found that at the time of the mass kill the concentrations of free chlorine in the cooling water reached levels as high as 6 ppm—approximately 12 times the normal level (H.H. Carter, personal communication).

A massive kill of blue crabs (*Callinectus sapidus*) occurred in the discharge canal near the end of August, 1966. It was estimated that there were at least 40,000 dead crabs, both juveniles and adults, in the canal (Mihursky, et al, 1967). Temperatures in the canal are not available for this period, but the water temperature at a location approximately 0.3 km off the mouth of the canal reached a maximum temperature of 34.6°C (Mihursky, et al., 1967). Many of the dead crabs were discolored, and Mihursky, et al. (1967) suggested that "The reddish color of many crabs may indicate a heat kill; however, at this time we cannot rule out the possibility of a chemical kill." Temperatures in the canal probably did not exceed 36°C.

Crabs are among the most temperature-tolerant of all Chesapeake Bay organisms. The temperatures in the canal were however, near the lethal limit for blue crabs (Tagatz, 1969). Tagatz acclimated blue crabs to various temperatures for 21 days and then exposed adult and juvenile crabs to test temperatures at 2°C intervals near the estimated upper and lower limits of their temperature tolerances for 48 hours. The results of Tagatz's experiments with adult female crabs in 20% sea water are shown as a tolerance diagram in fig. 8, which is a plot of lethal temperatures (temperatures at which 50% mortality occurs after 48 hours) against acclimation temperatures. The area inside the curve represents the thermal possibilities un-

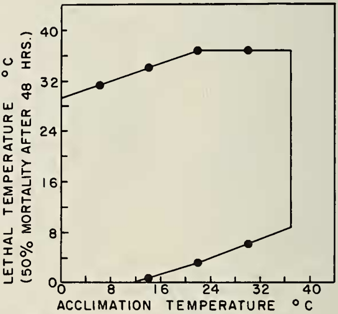


Fig. 8. Thermal tolerance of adult (mature female) blue crabs in 20% seawater (after Tagatz, 1969).

der which adult crabs survive for a presumably indefinite time. The results of Tagatz's experiments indicate that crabs in the canal were probably near their upper lethal limit—about 36°C—at the time of the kill. Temperatures in the canal were probably near 36°C for a number of days, and since the crabs had to work to stay in the discharge canal, there may have been an additional and important stress. Crabs do not turn red at temperatures of 36°C. They can turn red however, when free chlorine levels are high. In view of this, and the more recent evidence of a chlorine kill of finfish, it seems likely that the crab kill may have been caused by a combination of factors—temperature and chlorine. The additional stress of high chlorine levels on organisms living near their upper limit of temperature tolerance may have been sufficient to produce the massive kill. Unfortunately, the plant's chlorination and temperature records are no longer available for examination.

The only unequivocally documented ecological effects of the waste heat from the Chalk Point plant are the mortalities of plankton which occur during passage through the plant and discharge. The extent of such mortalities is increased by the poor design of the discharge system. The time of passage through the canal is excessive—nearly 2½ hours—and there is very little cooling within the canal. Organisms are subjected to excess temperatures of greater than 5°C for about 2½ hours.

The comments above are not meant to imply that there are no subtle, long-term ecological effects from the observed increases in temperature. These can only be documented through very careful and detailed long-term studies. Their documentation will be difficult however, because man is affecting the Patuxent estuary in other ways. The concentrations of nutrients in the upper Patuxent have risen markedly in the past 10 years, the concentration of inorganic nitrogen has increased by at least an order of magnitude, and there has been a substantial increase in the level of inorganic phosphorous.

Another power plant which has received a considerable amount of attention is the Calvert Cliffs Nuclear Power Plant which is being built by the Baltimore Gas and Electric Company. The plant is scheduled to begin operations some time in 1973. The plant design calls for two nominal 875 MWE units. The predicted rate at which heat will be rejected to the environment is about 5.0 x $10^{10}$ cal/sec (1.2 x $10^{10}$ BTU/hr). At a temperature rise across the condensers of 5.5°C, approximately 153 $m^3$/sec of cooling water will be required. This represents approximately 6% of the available water. The cooling water will be drawn into the plant from the Bay below 8 m and discharged as a submerged jet. The time of travel from the point of intake to the point of discharge is about 3 minutes.

Pritchard (1969) has made first-order estimates of the probable distribution of excess temperature that will be produced by the Calvert Cliffs plant. The predicted horizontal distribution of excess temperature in the layer having maximum excess temperature is presented in fig. 9. The distribution is for the end of a flood period. On the ebb tide the plume will be bent over and elongated down the Bay.

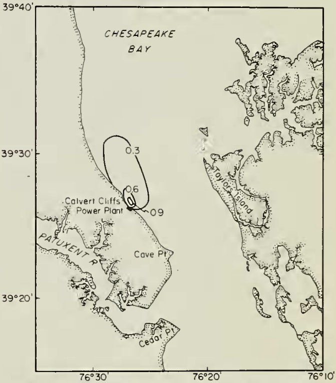


Fig. 9. Estimate of horizontal distribution of *excess* temperature, °C, in vicinity of Calvert Cliffs Nuclear Power Plant, for the period of flood tide (from Pritchard, 1969).

The vertical distribution of excess temperature at slack water along the axis of the

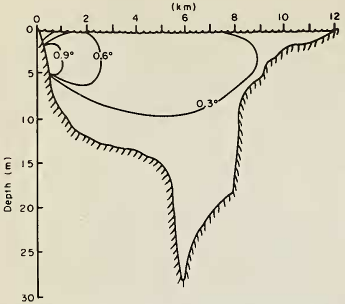


Fig. 10. Distribution of excess temperature, °C, on a vertical section along axis of plume at slack water (from Pritchard, 1969).

plume is shown in fig. 10. The predicted mean sectional excess temperature in the tidal segment of the Bay opposite the plant is about 0.2°C, and only about 1% of the entire cross-section adjacent to the plant will have excess temperatures greater than 1°C.

Clearly, the impact of the Calvert Cliffs Plant on the temperature distribution of the adjacent Bay will be much less than that the Chalk Point Plant now has on the temperature distribution of the Patuxent. The biological effects should also be less. The mortality rate during entrainment should be considerably lower, since the time of entrainment is only about 3 minutes compared to 2½ hours at the Chalk Point Plant.

In summary, there are marked natural, temporal, and spatial variations of water temperature throughout the Chesapeake Bay estuarine system. Superimposed upon the natural temperatures are the "excess temperatures" which result from the discharge of condenser cooling water from power plants. These excess temperatures can be predicted and determined with a reasonable degree of accuracy. The ecological effects of the man-made temperature elevations however, are more difficult to ascertain. No significant ecological damage to the Chesapeake Bay has been unequivocally documented from *present* inputs of heated discharges, nor is any likely to occur from the plants now under construction (Fig. 5). But additional plants will be needed. Man's power consumption is increasing at an alarming rate—a doubling approximately every decade.

### Salinity

Salinity is important because of its affect on density, and on a number of other important physico-chemical properties. Salinity is also very important biologically. It exerts a marked influence on the distribution and activity of many organisms that inhabit the Bay.

The distribution of salinity in the main body of the Bay and its tributaries has been studied by the Chesapeake Bay Institute for over 20 years. The results have been presented in a series of graphical summary reports (Whaley and Hopkins, 1952; Stroup and Lynn, 1963; Seitz, 1971).

The spatial and temporal distributions of salinity in the Chesapeake Bay and its tributary estuaries are determined by the freshwater inflow. The mixing of the freshwater and the seawater is produced primarily by tidal action, with the total freshwater inflow to the Chesapeake Bay system averaging approximately 1950 $m^3$/sec from 1951 through 1970. The major source of freshwater is the Susquehanna River, which accounts for approximately 50% of the total input of freshwater. The discharge of the Susquehanna accounts for more than 90% of the total freshwater input above Annapolis and more than 85% of the freshwater entering the Bay above the mouth of the Potomac. The Susquehanna has a long-term (38-year) annual average flow of about 985 $m^3$/sec. The range in the annual average flow of from about 550-1525 $m^3$/sec represents a fluctuation about the 38-year mean flow of greater than ± 44%. The yearly averages show a standard deviation greater than 20% of the 38-year mean. Seasonal fluctuations in the average flow are even greater; the minimum monthly discharge averages about 215 $m^3$/sec, and the maximum monthly flow averages approximately 3256 $m^3$/sec. Relatively large short-term fluctuations also occur. For example, during March of 1964 the average discharge of the Susquehanna was approximately 4200 $m^3$/sec, while the

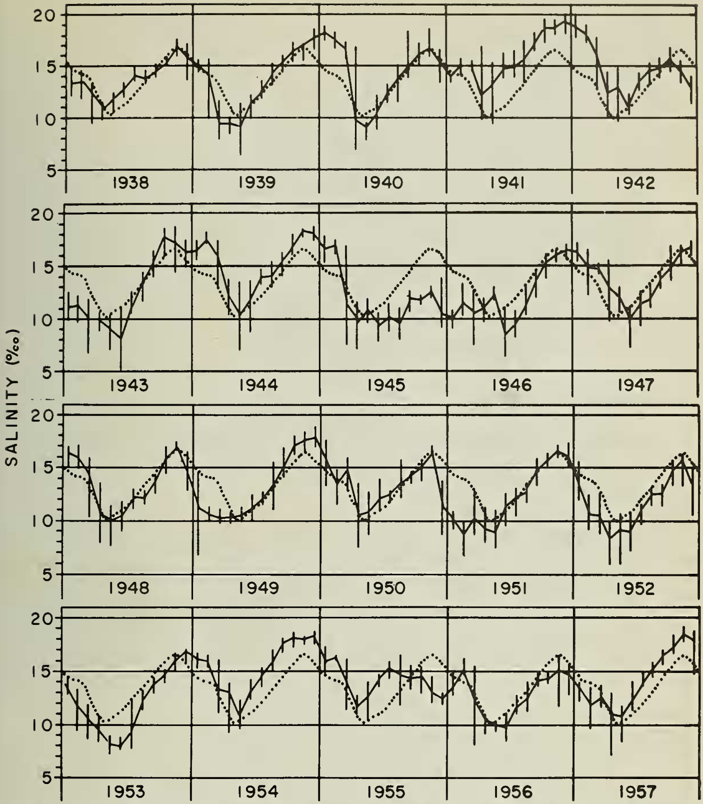


Fig. 11. Surface salinity at Solomons in the Patuxent estuary between 1938 and 1957. The monthly means are connected by solid lines, the monthly extremes are indicated by vertical lines, and the dotted curve represents a moving ten-day average of twenty-year daily means (from Beaven, 1960).

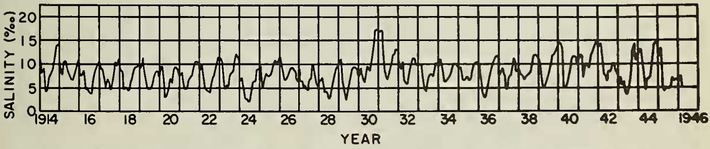
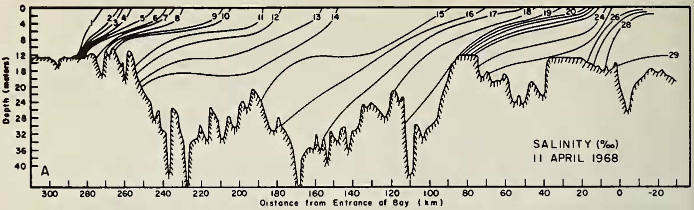


Fig. 12. Monthly average salinities at Fort McHenry in Baltimore Harbor between 1914 and 1948 (from Beaven, 1946).



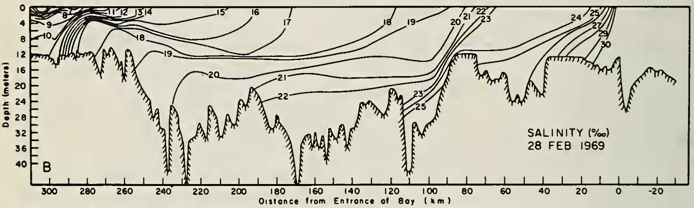


**Fig. 13A (above). Longitudinal salinity distribution along axis of Chesapeake Bay during a period of high river flow (from Seitz, 1971).**

**Fig. 13B (below). Longitudinal salinity distribution along axis of Chesapeake Bay during a period of low to moderate river flow (from Seitz, 1971).**

maximum daily discharge during the month was about 14160 $m^3$/sec. At present there is no significant regulation of the flow of the Susquehanna.

The second largest river debouching into the Bay is the Potomac, which contributes approximately 16% of the total freshwater input to the Bay. The Potomac has a long-term average discharge of about 310 $m^3$/sec. It is a flashy river with a recorded range in flow of 20 $m^3$/sec to about 1360 $m^3$/sec. There is no significant regulation of its flow. The third largest source of freshwater is the James River.

The marked variations of the freshwater inflow produce large temporal variations of salinity. The variations are most marked, of course, in the upper reaches of the Bay and its tributary estuaries. Near Pooles Island in the upper Chesapeake Bay the salinity during 1960, a year of relatively high river flow, ranged from 0.4‰ in April to 8.3‰ in December—more than a 20-fold range. During 1964, a year of relatively low river flow, the range in salinity was from 0.8‰ in March to 13.3‰ in December.

Long-term records of the variations of salinity observed at 2 stations in the Bay are shown in figs. 11 and 12. Fig. 11 is a record of the monthly mean salinities, and the extremes, at Solomons, Maryland, near the mouth of the Patuxent estuary between 1938 and 1957 (Beaven, 1960). A curve is also shown depicting the results of a moving 10-day average of the 20-yr daily mean salinities.

Fig. 12 is a plot of the monthly average salinity values between 1914 and 1945 at Fort McHenry in Baltimore Harbor (Beaven, 1946). These figures show relatively large monthly, seasonal, and longer-term variations in salinity at these locations.

The longitudinal variation in surface salinity over the length of the Bay ranges from the salinity of the Susquehanna River water, about 0.1‰, near the head of the Bay to a salinity of about 25-30‰ at the mouth. The longitudinal distribution in the Bay for a period of high river flow is shown in fig. 13A, and for a period of low to moderate river flow in fig. 13B. During periods of high flow, the "mouth" of the Susquehanna may be extended to a point nearly 45 km into the main body of the Bay. During such periods the transition from river to estuary is marked by a sharp front separating the fresh river water from the salty estuary water. Salinity gradients greater than 5‰ in 5 km are not uncommon in the frontal regions. With subsiding river flow the characteristic 2-layered net circulation regime is reestablished in the upper Bay. Salt is advected into the region by the lower layer and the salinity distribution illustrated in fig. 13A is transformed to resemble that shown in fig. 13B—the distribution characteristic of 2-layered estuarine circulation regimes. The rate of recovery is not well known, but it is almost certainly less than 1 week and may be only a few tidal cycles.

There are, then, marked natural spatial and temporal salinity variations. The changes are greatest in the upper reaches of the estuaries, but relatively large variations occur throughout the Chesapeake Bay estuarine system.

To date, man has had little effect on the salinity distribution in the Bay or its tributaries. Recently, however, there has been concern over the possible effects of the enlargement of the Chesapeake and Delaware Canal on the salinity distribution and on the ecology of the upper Chesapeake Bay. The Canal channel is being widened from 76 m to 137 m, and deepened from 8.2 m to 10.7 m.

Because of differences in the tidal characteristics at the Chesapeake and Delaware ends of the Canal, there is a net non-tidal flow through the Canal from the Chesapeake Bay to the Delaware Bay. Pritchard (1971) estimated that the net non-tidal eastward flow through the 8.2-m-deep Canal is about 28 $m^3$/sec, and he predicted that the net flow through the enlarged Canal would increase by a factor of 2.7 to about 76 $m^3$/sec. The tidal velocities and the tidal excursions, which may be of greater ecological significance than changes in the net volume rate of flow, will be increased by a factor of only about 1.2.

Using a 1-dimensional time-dependent numerical model of the salinity distribution in the upper Chesapeake Bay developed by Boicourt (1969), Pritchard (1971) made estimates of the probable effects of the enlargement of the Canal on the Salinity distribution. His analysis showed that the increased diversion of freshwater through the Canal to the Delaware Bay would have very little effect on the salinity distribution during periods of high river flow when salinities are at a minimum. The average minimum salinity would probably increase from 8.60 to 8.79‰ at the Bay Bridge, from 1.14 to 1.19‰ at Pooles Island, and would be unchanged, 0.13‰, at Turkey Point. The greatest effects would, of course, be observed during periods of very low river flow when salinities are a maximum. Pritchard (1971) predicted that the average maximum salinity would probably be increased from about 17.23 to 17.62‰ at the Bay Bridge, from 9.00 to 11.58‰ at Pooles Island, and from 2.14 to 2.94‰ at Turkey Point.

Changes in the salinity distribution in the upper Bay would also result from flow regulation of the Susquehanna River. Flow regulation would reduce the natural variations of the spatial and temporal salinity distributions in the upper Chesapeake Bay, and therefore the variations in the associated circulation patterns in the upper Bay and in a number of the tributary estuaries.

The temporal variations in salinity in the upper Bay provide the basic mechanism for the flushing of tributary estuaries such as the Gunpowder, Bush, Back, Magothy, and Severn (Pritchard, 1968). The small freshwater input to these tributaries is insufficient to maintain a steady circulation pattern, and the water that fills them is derived largely from the adjacent Bay. It is only in the upper reaches of these tributaries that the salinity distribution is significantly affected by the freshwater inflow. The primary factor controlling the exchange of water between these tributaries and the Bay is the temporal variation in the salinity of the upper layer in the adjacent Bay. The salinity of the surface layers of the upper Bay varies seasonally with maximum values in the fall and minimum values in the spring. The salinity changes in the tributaries lag behind those in the adjacent Bay. During winter and early spring when the salinity in the

Bay is decreasing with time, the salinity in the tributaries is, at any given time, higher than in the Bay. As a result water flows into the tributaries at the surface from the Bay, and out of the tributaries in the deeper layers into the Bay. In late spring, summer, and early fall when the salinity of the Bay is increasing, the salinity in the tributaries is less than in the adjacent Bay, and hence the waters of the tributaries flow out at the surface, while Bay waters flow into the tributaries along the bottom. Since these estuaries are shallow—channel depths generally less than 6 m—only the upper layer of the Bay participates in the exchange with the tributaries.

The circulation pattern in these tributaries is thus reversed at least twice each year. Some of the smaller estuaries tributary to the head of the Bay, such as the Gunpowder and the Bush, are renewed more often. These estuaries are subject to rapid renewal rates because of large, short-period fluctuations in the salinity of the adjacent Bay;

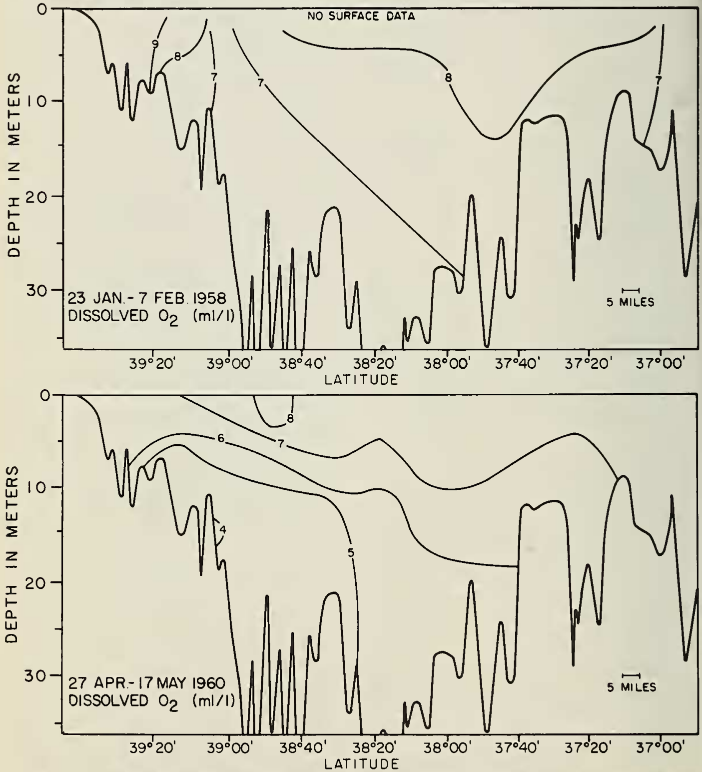


Fig. 14. Longitudinal distribution of dissolved oxygen along axis of Chesapeake Bay during winter (above) and spring (below).

fluctuations produced by sudden, marked changes in the discharge of the Susquehanna River. Pritchard (1968) has pointed out that if the flow of the Susquehanna were controlled to the extent that the seasonal changes in salinity in the upper Bay were to disappear, the primary mechanism for the flushing of a number of the small tributaries would disappear, and pollution problems would be intensified.

In summary, there are marked natural temporal and spatial variations of the salinity particularly in the upper reaches of the Bay and its tributary estuaries. To date, man has had little effect on the distribution of salinity in the Chesapeake Bay estuarine system.

### Dissolved Oxygen

Dissolved oxygen is added to the water by exchange across the air-sea interface (naviface) and by photosynthesis. Oxygen is removed from the water by loss across the naviface, by respiration, by oxidation of or-

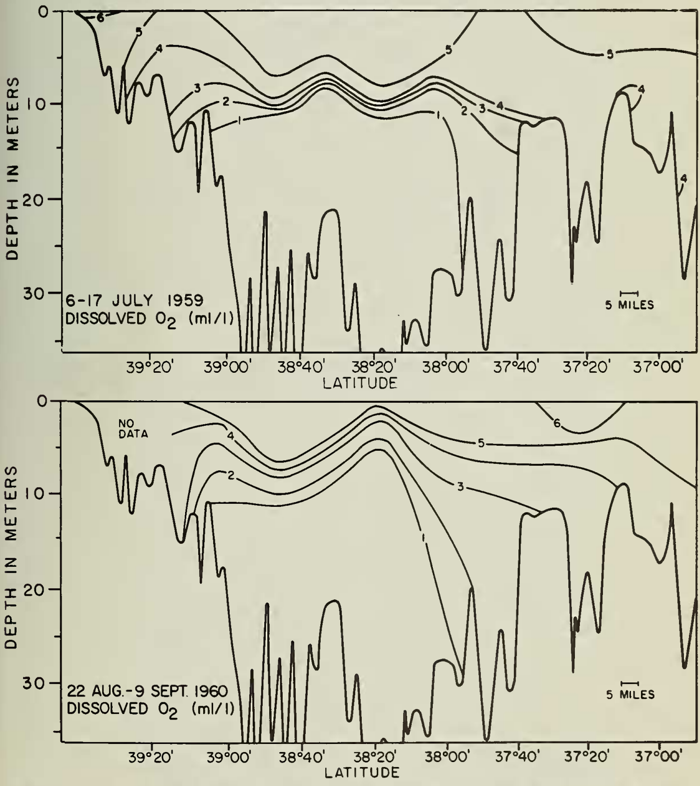


Fig. 15. Longitudinal distribution of dissolved oxygen along axis of Chesapeake Bay during summer.

ganic matter, and by reactions with reduced materials such as sulfides, and iron[I]. Dissolved oxygen is removed from all depths, but it is added only to the upper part of the water column–to the depth of the euphotic zone. There are marked natural variations in the temporal and spatial distributions of dissolved oxygen. Near the surface of most of the estuary, the values stay near saturation throughout the year, but in the lower layer the concentrations of dissolved oxygen may go from near saturation to near 0 over the year. Superimposed upon these natural variations are fluctuations resulting from man's activities.

The natural variations are explainable in terms of the characteristic physical, chemical, and biological processes. We will examine the seasonal variations of dissolved oxygen along an axial section of the Chesapeake Bay, (figs. 14-15). During the winter the water is cold, saturation values are high, and mixing is relatively intense. The estuary is nearly uniformly high in dissolved oxygen content throughout the water column. In the spring, the water temperatures rise in response to increased solar insolation and warm spring rains. Because of the increased water temperatures, saturation values of dissolved oxygen decrease. Near the surface the concentrations of dissolved oxygen stay near saturation, but in the lower layer the values decrease more rapidly than at the surface, and soon become much less than the saturation values. In the early spring the river flow increases because of increased precipitation and melting snow. The additional freshwater inputs increase the stability of the water column, thereby decreasing the vertical mixing. The source of oxygen to the lower layer has thus been greatly diminished. Utilization of oxygen, however, increases with increasing temperature. By mid-June the concentration of dissolved oxygen in the deeper layers of the Bay may be less than 1 ml/l, while the surface values which are near saturation may be greater than 5 ml/l. This condition continues throughout the summer months. By mid-summer the concentration of dissolved oxygen at depths greater than 12 m may be less than 0.1 ml/l. Anaerobic conditions have not been observed in the main body of the Bay, but the deeper areas of a number of the tributaries including the Severn, the Potomac, and Eastern Bay go anaerobic in the summertime.

In late summer, usually near the end of August, rapid changes in the vertical distribution of dissolved oxygen often occur. A few clear, cool nights cool the surface waters sufficiently to increase their density above that of the underlying water. Vertical downward mixing is initiated and the deeper water is thus replenished with dissolved oxygen. Another warm spell may re-establish a strong vertical density gradient, and the oxygen in the deeper layer will again decrease. By the middle of October the concentration of dissolved oxygen has started to increase steadily at all depths, and within a few weeks the Bay becomes nearly uniform in dissolved oxygen.

There are also diurnal variations of the concentration of dissolved oxygen in the euphotic zone. Values are higher during the daylight hours of photosynthetic activity than during the hours of darkness when photosynthetic production of oxygen ceases but respiratory consumption continues. The "natural" diurnal variations are generally small, but in highly productive areas they may be large.

Superimposed upon these natural fluctuations are variations resulting from man's activities. These effects have resulted largely from the introduction of nutrients which stimulate primary productivity and are most readily observable in the upper reaches of some of the tributary estuaries. When nutrients are no longer limiting, solar energy is, and there is frequently a sequence of intense blooms separated by massive die-offs. The die-offs produce large oxygen depletions, sometimes resulting in anaerobic conditions. Low oxygen zones in the tributaries probably began to increase in frequency, duration, and extent as early as the latter part of the 18th century as a result of increased agriculture. The additional nutrients introduced into the triburaries stimulated primary productivity. The organic detritus placed heavy oxygen demands on the estuaries. The nutrients in the sewage and municipal wastes of a burgeoning population have seriously

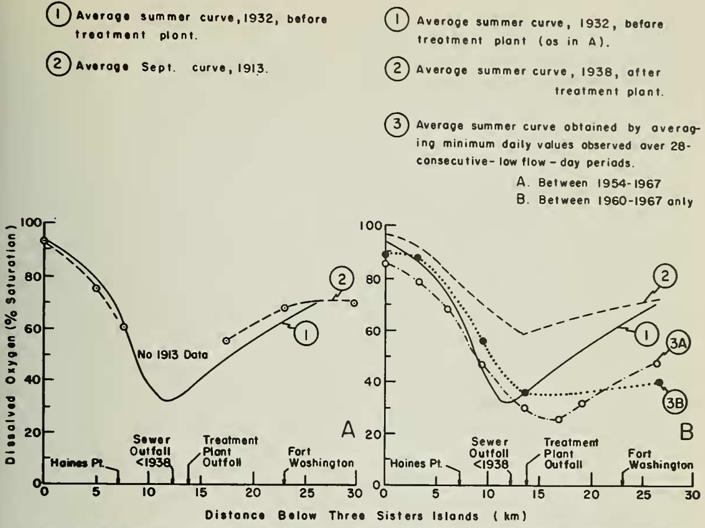


Fig. 16. Longitudinal distributions of dissolved oxygen in tidal reaches of Potomac. Fig. at right after Wolman (1971).

aggravated the problem in a number of the tributaries.

The effects of man on the distribution of dissolved oxygen are readily apparent in the Potomac, particularly in the tidal reaches of the River below Washington, D.C. Large amounts of nutrients added by the metropolitan Washington area sewerage system to an already enriched Potomac result in a high level of primary productivity and large biochemical oxygen demands (BOD).

Recently Wolman (1971) reported some observations of dissolved oxygen made between 1932 and 1967 in the tidal reaches of the Potomac River. He presented a curve depicting an average longitudinal variation of dissolved oxygen minima expressed as % saturation for the summer of 1932 before construction of the Washington treatment plant, and a similar curve for the summer of 1938 following construction of the treatment plant. He also presented a curve of the average longitudinal distribution of dissolved oxygen minima obtained by averaging the lowest daily oxygen values observed over 28-consecutive-day periods of minimum river flow between 1954 and 1967. A similar curve was plotted for 1960-1967 only. These curves are shown in fig. 16. Fig. 16 shows a curve depicting the average distribution of dissolved oxygen in 1913 during the month of September, the month of lowest oxygen levels (Cumming, et al., 1916). All of the curves in fig. 16 show a sag in the oxygen levels below Washington. There were no 1913 data in the region of the sewer outfall. Upstream from the outfall, the 1913 oxygen levels were slightly lower than the 1932 levels while downstream from the outfall they were slightly higher. The differences may not be significant, but the higher levels in 1913 downstream from the sewer outfall might be explained by the dense growth of submerged vegetation that covered nearly all of the bottom outside of the channel in 1913 but which disappeared in the 1920's.

In 1938, following construction of the Blue Plains sewage treatment plant, the oxygen levels rose significantly, but the therapeutic effects of the plant were apparently relatively short-lived. The average oxygen minimum curve for periods of low flow between 1954 and 1967 indicates that not only had the concentrations of dissolved oxygen apparently decreased to levels below those observed before any treatment was provided, but the zone of low oxygen extended farther downstream. For the period 1960-1967 the situation was apparently slightly improved.

The trends indicated by the curves in fig. 16 are very probably real, but one must, for a number of reasons, be prudent in comparing these observations which span 54 years: the accuracy and precision of the measurements are uncertain; the averaging processes used by the investigators are obscure; and the diurnal fluctuations of the concentration of dissolved oxygen which are appreciable in this region were apparently not considered in sampling.

Improvement of the levels of dissolved oxygen in the tidal reaches of the Potomac presents a formidable challenge. As Wolman (1971) pointed out, "Despite expenditures upward of $70 million from 1938 through 1965, in recent years dissolved oxygen during the summer months has retreated to the position occupied by similar curves in 1932 before major treatment works were installed in 1938." The low concentrations of dissolved oxygen result from massive die-offs of intense blooms which are stimulated by the high nutrient levels. Even if all of the nutrients were to be removed from the Washington metropolitan area waste effluent, the nutrient levels in the River would still be at an undesirable level.

In summary, man's activities have certainly increased the frequency, extent, and duration of low oxygen zones in the upper reaches of the Potomac and of a number of other tributaries. Because of the lack of historical data, however, it is not possible to chronicle these changes.

Low levels of dissolved oxygen are a symptom of a much more serious problem, probably the most serious, that threatens the Bay—the influx of nutrients from municipal and agricultural wastes.

### Nutrients

The nutrients nitrogen and phosphorous are necessary for primary productivity. They are added to the Chesapeake Bay estuarine system by natural sources and as a result of man's activities. They have not only always been present in the Chesapeake Bay and other estuaries because of their natural sources, but have probably, because of the dynamic processes in the estuary, always been present in relatively high concentrations—high relative to other parts of the marine environment. But large additional inputs of nitrogen and phosphorous have been added to the Chesapeake Bay and other waterways by man's activities. It has been estimated that the total amount of phosphorous discharged into United States waterways probably exceeds that of 50 years ago by a factor of 3 or 4 (Man's Impact on the Global Environment, 1970). Large amounts of nutrients are introduced directly into the Chesapeake Bay estuarine system through the discharges of municipal treatment plants. In addition, rivers convey large quantities of nutrients into the Bay—nutrients which result in large part from man's activities in the drainage basin, perhaps hundreds of kilometers away. Nutrients are added to the rivers in sewage, in runoff from fertilized fields, and from animal feedlots.

Both nature and man concentrate their effects on the tributaries and on the upper reaches of the Bay. These zones have buffered man's impact on the main body of the Bay, but many of them have been degraded by undesirably high levels of productivity stimulated by high nutrient concentrations.

In the Maryland portion of the Bay the effects of nutrient-loading from municipal wastes are most apparent in the upper Potomac and in Back River; the receiving waters for the wastes from the metropolitan Washington, D.C., and Baltimore areas. The dramatic increases in nutrient levels which have recently been reported in the upper Patuxent (Flemmer, 1971) are a result of the wastes from the burgeoning population in the small drainage basin of that river. The effects of local inputs from the septic field drainage of largely unsewered land areas are observable in some of the smaller tributaries including the South, Magothy, Miles, Chester, and Severn estuaries. In the upper reaches of the main body of the Bay, the Susquehanna is the major conveyor of nutrients—nutrients derived from extensive agricultural areas and from a population that exceeds 1 million in the drainage basin.

Assemblages of primary producers are adjusted to certain ranges of the concentrations of the essential nutrients and to certain ranges of their relative abundances. The limits of the ranges characteristic of "unpolluted" and "polluted" waters have not been firmly set. Some guidelines are necessary, however. After examination of the literature and discussion with several of my colleagues, the following conclusions were tentatively determined. In unpolluted, productive waters the ratio of total N to total P probably does not fall below 10:1, and the limit may be 15:1. In addition, concentrations of total P greater than about 3 $\mu$ g at./l are probably undesirable.

The Potomac River with an average flow of about 310 $m^3$/sec is the second largest river discharging into the Chesapeake Bay estuarine system. It is a flashy river with no significant flow regulation; the recorded flow range is from about 20 $m^3$/sec to 1360 $m^3$/sec. The Potomac drains approximately 28,490 $km^2$ of forested and agricultural land above Washington and 5,180 $km^2$ of urban area within the metropolitan Washington area. The transition from the Potomac *estuary* to the Potomac *River*, marked by the upstream limit of sea salt, occurs between 80-100 km above the mouth of the estuary. This is approximately 35-55 km below Washington, D.C. The tidal effects extend farther upstream to the fall line just above Washington. The freshwater region between the upstream limit of sea salt and the head of tide is called the "tidal reaches of the river."

Nutrients are introduced into the upper reaches of the Potomac *River* by drainage of agricultural areas and by additions of sewage. Measurements made in 1965-1966 showed that in the river just above Washington the concentrations of nitrate were 100-150 $\mu$g at./l during periods of high river flow, and the concentrations of phosphate about 5 $\mu$g at./l (Carpenter, et al., 1969). During periods of low river flow the concentrations of nitrate were about 50-70 $\mu$ g at./l, and the concentrations of phosphate about 3-4 $\mu$ g at./l. THe levels of phosphorous in the River are already at undesirable levels, even before the river reaches Washington, D.C.

The sewerage systems of the Washington metropolitan area presently discharge into the Potomac River about 1.1 x $10^6$ $m^3$/day (290 MGD) containing more than 6 metric tons of phosphorous and 10 metric tons of nitrogen, and these values are expected to double within 30 years. Probably more than half of the phosphorous is from phosphate in detergents. These inputs produce very high local concentrations of nutrients, particularly during periods of low river flow. For example, with a river flow of about 85 $m^3$/sec, the input of sewage would increase the concentrations of phosphorous by about 180 $\mu$ g at./l (Carpenter, et al., 1969). During 1965 the river flow exceeded 85 $m^3$/sec less than 1/3 of the time. These high concentrations of nutrients do not extend very far downstream; they are primarily restricted to the tidal reaches of the river.

Carpenter et al., (1969) have described the distributions of nutrients in the Potomac, and this discussion is based in large part on their report. The longitudinal distribution of nutrients in the Potomac varies seasonally, with concentrations of total nitrogen in the *estuary* generally being highest during January, February, and March, (fig. 17).

The monthly longitudinal distributions of total phosphate show increases in the tidal reaches of the river during late fall and winter, displacement of the high values downstream into the estuary with increasing flow in the spring, and then relatively moderate and uniform concentrations in the estuary throughout the summer and most of the fall, (fig. 18). The concentrations of inorganic phosphate are high in the tidal reaches of the river and constitute an appreciable fraction of the total phosphate concentrations. Farther downstream in the estuary, however, inorganic phosphate concentrations exceed 0.5 $\mu$ g at./l only after high river flow.

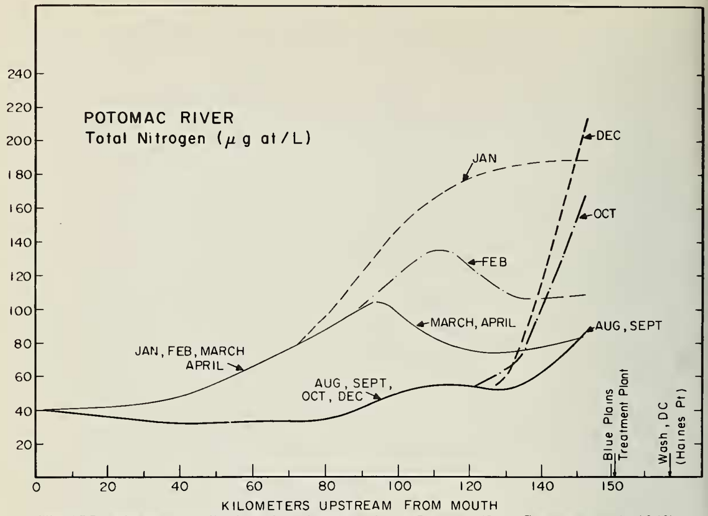


Fig. 17 Longitudinal distribution of total nitrogen in the Potomac (from Carpenter, et al., 1969).

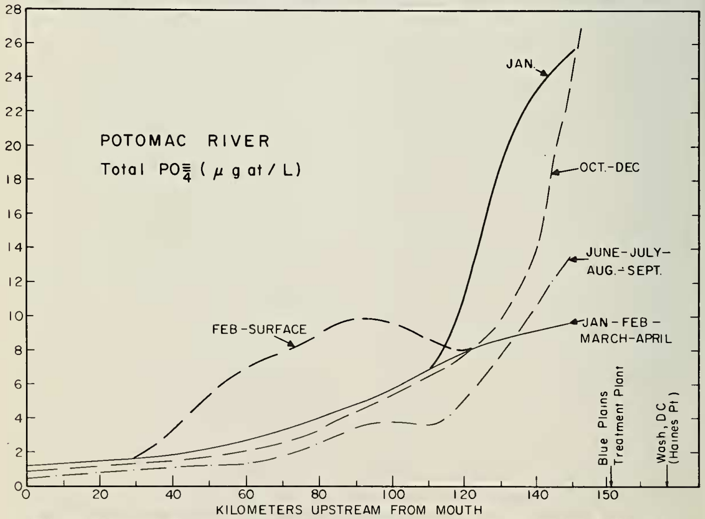


Fig. 18. Longitudinal distribution of total phosphate in the Potomac (from Carpenter, et al., 1969).

In the tidal reaches of the Potomac River the concentrations of total phosphorous are at undesirably high levels, and the ratio of nitrogen to phosphorous is lower than in "healthy" productive waters. Farther seaward, in the estuary, the concentrations of phosphorous fall below 3 $\mu$ g at./l, and the ratio of N to P is greater than 10:1. The nutrient patterns are reflected in the longitudinal distributions of chlorophyll, which show very high concentrations in the tidal reaches of the River—concentrations which frequently exceed 70 $\mu$ g/l. These high values are produced primarily by *Microcystis aeruginosa*. These organisms collect in mats along the shoreline, producing repugnant conditions. In the estuarine sections of the Potomac chlorophyll levels are appreciably lower and are comparable to those in the upper Chesapeake Bay.

Clearly man has had a major and undesirable effect on the nutrient levels in the upper Potomac. Historical data are not available to chronicle the evolution of this impact, but one can get some idea of the inputs of nutrients from the Washington area by examining the population and waste water records. The Washington metropolitan area treatment plant (Blue Plains) was constructed in 1938. Prior to this, Washington had a sewerage system but did not have a treatment plant. In 1970 the treatment plant served a population of about 1.8 million and discharged approximately 1.1 x $10^6$ $m^3$/day (290 MGD) into the Potomac. This waste water contributed approximately 6 metric tons of phosphorous and 10 metric tons of nitrogen to the Potomac each day. In 1970 Washington, D.C. had a population of 756,510. In 1940 the Blue Plains treatment plant served a population of about 0.8 million and discharged approximately 0.4 x $10^6$ $m^3$/day (100 MGD). At that time Washington, D.C. had a population of 663,091. If the concentrations of phosphorous and nitrogen in the waste water were the same in 1940 as in 1970, this would represent daily inputs of about 2 metric tons of phosphorous and 3 metric tons of nitrogen. The concentrations of nutrients were probably less in 1940 than in 1970, but even if they were only 50% of the 1970 values, these lower inputs would result in undesirably high nutrient levels. The oxygen data, discussed elsewhere in this paper, also suggest that problems of eutrophication in the upper Potomac are of long standing. Following the introduction of soap powders containing phosphorous *circa* 1938, the concentrations of phosphates in the tidal reaches of the Potomac probably rose significantly, but they have probably been at undesirable levels for well over 50 years.

In some other tributaries the increases of nutrient concentrations to undesirable levels have been much more recent. In the upper Patuxent the concentrations of inorganic nitrogen increased by 10-15 times between 1962-64 and 1971, and inorganic phosphorous has also shown substantial increases over this period (Flemmer, 1971). The concentrations of nutrients in the upper Patuxent frequently reach levels comparable to those in the upper Potomac. The standing crop, as measured by chlorophyll, has increased, but not to the point of nuisance blooms such as those occurring in the upper Potomac (Flemmer, 1971).

In the main body of the upper Chesapeake Bay the nutrients are derived primarily from the inflow of the Susquehanna River. The upper Chesapeake Bay is the estuary of the Susquehanna River. The Susquehanna, with a long-term average flow of about 985 $m^3$/sec, discharges more than 85% of the total freshwater into the Bay above the mouth of the Potomac. The Susquehanna drains about 71,225 $km^2$ of New York, Pennsylvania, and Maryland. The watershed has extensive agricultural areas and a population of more than 1 million. These sources combine to contribute large quantities of nitrogen and phosphorous to the river (Carpenter, et al., 1969). The inputs are modified along the course of the river by biological removal which occurs in broad, shallow reaches of the river and in the series of reservoirs. When the river reaches the head of the Bay at Havre de Grace, Maryland, the concentrations of total phosphorous range from about 1.5 $\mu$ g at./l during winter and spring to about 1.0 $\mu$ g at./l during summer and fall. Nitrogen levels range from 80-105 $\mu$ g at./l during spring to

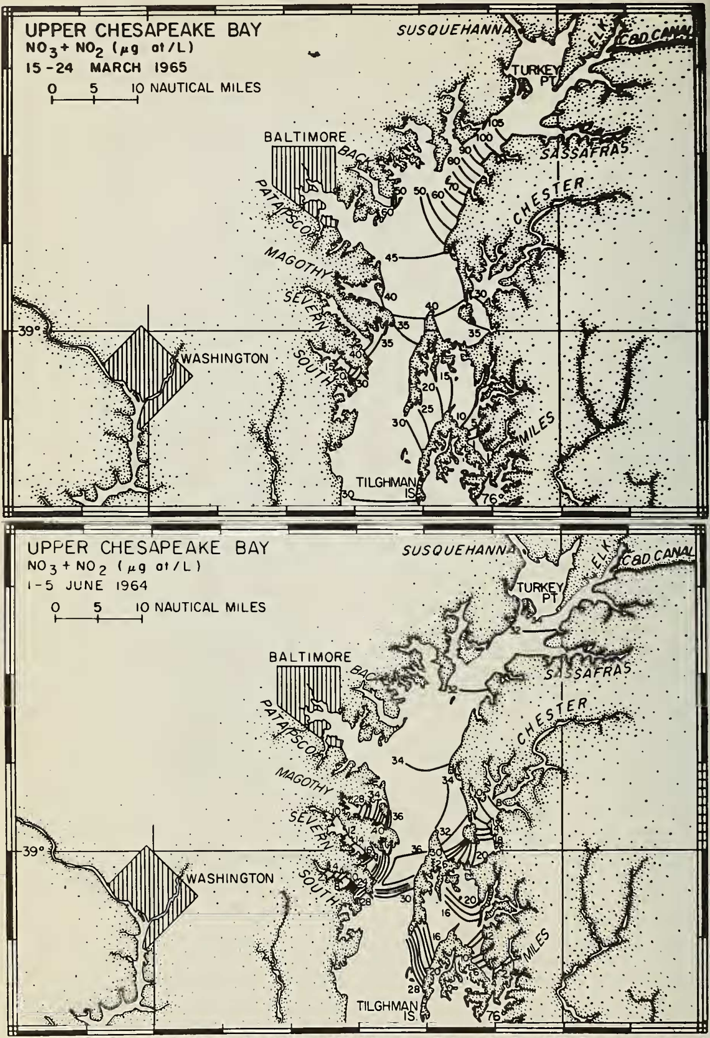


Fig. 19. Surface nitrate distributions ($NO_3 + NO_2$) in upper Chesapeake Bay (J.H. Carpenter, personal communication).

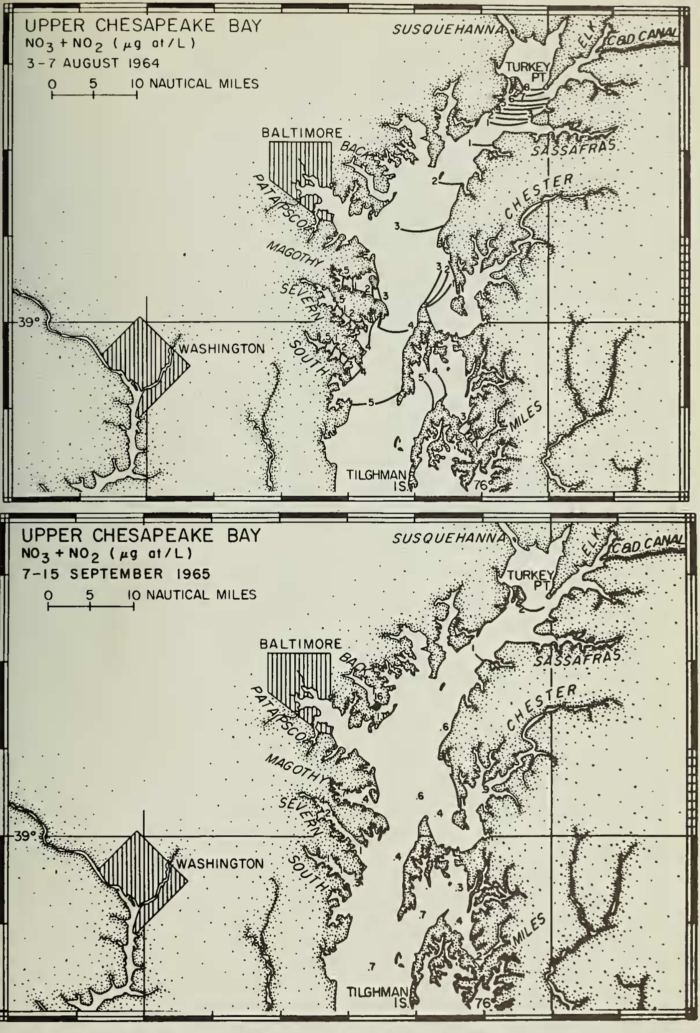


Fig. 20. Surface nitrate distributions ($NO_3 + NO_2$) in upper Chesapeake Bay (J.H. Carpenter, personal communication).

about 50 $\mu$g at./l during other seasons. Most of the nitrogen is present as nitrate.

The spatial distribution of nitrate in the upper Bay indicates that the Susquehanna River is the primary source, (figs. 19-20). Nearly half of the total annual flow of the Susquehanna occurs during a 3-month period in late winter and early spring. Since the nitrate concentrations are highest during this period, the Susquehanna discharges more than 60% of its total annual nitrate input during these 3 months. By the middle of April the Bay has a rather uniform nitrate distribution with concentrations of about 45 $\mu$g at./l. Throughout the late spring and summer the concentrations generally decrease and by September may be less than 1 $\mu$g at./l.

The distributions of phosphorous differ markedly from those of nitrogen. Total phosphate values are relatively uniform and have a range of only about 1-2 $\mu$g at./l. Phosphorous is apparently cycled at least twice between May and August, since the disappearance of some 45 $\mu$g at./l of nitrogen is not accompanied by changes in phosphate. During the summer more than half of the total phosphorous is present as dissolved organic phosphate.

In the main body of the upper Bay nutrient levels and phytoplankton production are high, but the grazing rate is also high thereby preventing an undesirable buildup of algae such as occurs in the tidal reaches of the Potomac. Nutrient levels are probably near the upper limit for "healthy" conditions. Pritchard (1968) estimated that a doubling of present nutrient levels in the main body of the Bay would produce undesirable conditions. A number of the upper Bay's tributaries are already over-enriched, and any additional inputs will be detrimental.

The municipal wastes from Baltimore are treated at the Back River treatment plant, which discharges about 0.6 x $10^6$ $m^3$ (150 MGD) of treated effluent each day. Of this, approximately 0.4 x $10^6$ $m^3$/day (100 MGD) are utilized by Bethlehem Steel as industrial cooling water and discharged into Baltimore Harbor. The remaining 0.2 x $10^6$ $m^3$/day (50 MGD) is discharged into Back River, a small estuary that is tributary to the Bay and located just north of Baltimore Harbor. Nutrient levels in Back River are very high, and blue green algae thrive. In 1965 chlorophyll concentrations exceeded 60 $\mu$g/l from March through November and reached levels of 400 $\mu$g /l in October. Eutrophication in Back River is intense, but the effects are restricted to the tributary and are not apparent in the adjacent Bay. There are marked decreases in chlorophyll and total phosphate near the mouth of the tributary—decreases greater than can be accounted for by dilution. Deposition of algal cells in the sediment is the most probable process of removal. The Back River estuary is acting as a type of tertiary treatment pond, and the sacrifice of this tributary has protected the main body of the Bay.

The waste ferrous sulfate added to the part of the effluent used as cooling water by Bethlehem Steel is apparently sufficient to precipitate the phosphate in the Harbor so that little of it reaches the Bay. The nitrate is apparently also being rapidly removed either by a component added to the effluent during its use as a cooling water, or by a constituent in the receiving waters, but the process by which this happens is not clear.

While the effects of the treated sewage discharged into Baltimore Harbor and Back River are readily observable in these tributaries, they are not apparent in the adjacent Bay. Carpenter et al., (1969) pointed out: "During the prolonged drought of 1965, discharge of the Susquehanna River was 4,000 $ft^3$/sec (113 $m^3$/sec) during July, August, and September. The admixture of this inflowing freshwater with seawater produced a density-driven circulation in the Bay off Baltimore with a flow in the upper layer of about 3 times the freshwater discharge, or 12,000 $ft^3$/sec (340 $m^3$/sec). This flow would provide a dilution for the sewage discharge of 1 to 50, which corresponds to a possible increase of 6 $\mu$g at. per liter of phosphorous and 36 $\mu$g at per liter of nitrogen in the mixture. Such increases are not observed in the bay."

In summary, man has had an appreciable effect on the distributions of nutrients in the Chesapeake Bay estuarine system, particularly in the upper reaches of the Bay, and of a number of the tributaries. In the Maryland portion of the Bay, nutrients are at undesirable levels in the upper Potomac and in Back River, and are near the upper limit in the upper Bay, the Patuxent and in many of the smaller tributaries. The discharge of improperly treated sewage and municipal wastes constitute the most serious immediate threat to the Chesapeake Bay estuarine system.

### Sediments

The general features of the geology of the Chesapeake Bay and the surrounding region have been discussed by Ryan (1953) and more recently by Wolman (1968). The characteristics of the bottom sediments have been described by Ryan (1953) and Biggs (1967). The sediments accumulating in the Bay are predominantly fine-grained silts and clays except in the littoral zone, where sand locally derived from shore erosion predominates (Ryan, 1953; Schubel, 1968a). The sources of sediment have been considered by Schubel (1968a, 1971a) and Biggs (1970), and the relationships between the circulation patterns and the sedimentation patterns have been investigated by Schubel (1971b).

The archenemy and ultimate conqueror of every estuary is the sediment that fills the basin and drives out the intruding sea. Sediments are introduced into the Chesapeake Bay by rivers, by shore erosion, by biological activity, and by the sea. The sources are thus external, marginal, and internal. Most of the inputs are poorly known. The only rivers for which reliable estimates are available are the Susquehanna (Schubel, 1968b; Schubel, 1972) and to a lesser extent the Potomac (Wolman, 1968). The Susquehanna discharges approximately 0.3-0.8 x $10^6$ metric tons/yr, while the Potomac probably discharges more than 2.3 x $10^6$ metric tons/yr. The sediment discharged by the rivers is fine-grained silt and clay. Most of it is trapped in the upper reaches of the estuaries by the net non-tidal circulation, which creates a very effective sediment trap in the transition zone where the net upstream flow of the lower layer dissipates until the net flow is downstream at all depths (Schubel, 1971b). Fine particles that settle into the lower layer are carried back upstream by its net upstream flow, leading to a rapid accumulation of sediment. The sedimentation rate in the upper Bay is probably at least an order of magnitude greater than in the middle and lower reaches of the Bay. Similar patterns exist in the tributary estuaries. Because of the net non-tidal circulation and the mixing there are also accumulations of *suspended* sediment in the upper reaches of the Bay and larger tributary estuaries. Such features, called "turbidity maxima", are characterized by turbidities and suspended sediment concentrations that are higher than those either farther upstream in the source river or farther seaward in the estuary. The turbidity maximum in the upper reaches of the Bay has been described by Schubel (1968c).

Since the Susquehanna is the only *river* that debouches directly into the main body of the Bay, it is the only major source of *fluvial* sediment to the Bay proper (Schubel, 1971a, b). Most of the sediment discharged by the other rivers is deposited in the upper reaches of their estuaries and does not reach the Bay proper. In the middle and lower reaches of the Bay, shore erosion is not only a major source, but probably the most important source of sediment (Schubel, 1968a, 1971; Biggs, 1970). The margins of the Bay are being digested at an alarming rate (Singewald and Slaughter, 1949; Schubel, 1968a).

The remains of the large populations of plankton, nekton, and benthos contribute little directly to the total accumulation of sediment. Filter-feeding benthos (Haven and Morales, 1966) and zooplankton (Schubel, 1971; Schubel and Kana, 1972), however, play an important role in the Bay's sedimentation. These organisms bind fine suspended particles into larger composite particles which are ultimately deposited. Without agglomeration many of the finer particles would not be deposited in the Bay but would be carried through the estuary and discharged to the ocean. Biological agglomeration is an important geological process.

Because of their circulation patterns, the

Chesapeake Bay and its tributaries are effective sedimentation traps, and sedimentation rates are naturally high. But man has markedly increased the sedimentation rates by increasing the inputs of sediment. With the clearance of forested land for agriculture in colonial days, sediment yields increased from an average of less than 35 metric tons/km$^2$/yr to 140-280 metric tons/km$^2$/yr (Wolman, 1967). Hundreds of thousands of acres of forested lands were cleared with axe and fire for tobacco farming. After 2 or 3 crops, the nutrients in the soil were depleted and new lands were needed for growing tobacco. The old fields were frequently abandoned and left bare to be eroded by the wind and rain. Much of the sediment was carried by streams and rivers into the estuaries tributary to the Bay.

Even before 1800, siltation was a serious problem in harbors such as Upper Marlboro on the Patuxent River, Port Tobacco on the Port Tobacco River (a tributary to the Potomac), and Joppa Town at the mouth of the Little Gunpowder. In the early 1700's Joppa Town was the county seat of Baltimore County and Maryland's most prosperous and important seaport. By 1750 the port had declined in importance, primarily because of sedimentation problems, and in 1768 the county seat was moved to Baltimore. Stone mooring posts that once held the hawsers of seagoing vessels are now 2 or more miles from navigable water (Gottschalk, 1945). According to Gottschalk (1945), who summarized observations on the sedimentation of colonial ports, the limit of open tidewater in Baltimore Harbor was 7 miles farther inland in 1608 when John Smith visited the Harbor than it is today.

In more recent years local sediment yields have been dramatically increased by imprudent land clearance for construction—yields sometimes reach 10,000 or even 35,000 metric tons/km$^2$/yr. It has been estimated that sediment from construction sites in the metropolitan Washington, D.C. area probably accounts for 25-30% of the total sediment load entering the Potomac at Washington (Wolman, 1968). Sediment derived from construction sites in the metropolitan Baltimore area is probably a major source of the sediment being discharged into Baltimore Harbor. After completion of urban construction projects, the new asphalt and concrete "land" may reduce sediment yields to levels well below those characteristic of forested regions.

But man's activities can also decrease the masses of sediment discharged into the Chesapeake Bay estuarine system. The construction of a series of dams along the lower courses of the Susquehanna River has decreased the quantities of sediment discharged into the upper Bay.

The effect of man's activities during the 18th and most of the 19th centuries was to increase sedimentation rates in the main body of the Chesapeake Bay and its tributary estuaries. In the latter part of the 19th century and during the 20th century, with better soil conservation practices, less land under cultivation, and the construction of a series of dams on the lower reaches of the Susquehanna, the overall sedimentation rate was decreased. In some tributaries, however, which drain areas of urban construction, the local sedimentation rates were greatly increased. The net effect of man's activities has been an increase in the overall "natural" sedimentation rate, but we can not say by how much.

In addition to the direct effects of filling the estuarine basin and thereby expelling the intruding sea, the fine-grained sediments have many indirect effects on the estuary. While suspended they limit the penetration of light, and therefore the depth of the euphotic zone and the primary productivity. Because of their high sorptive capacity, clay particles concentrate heavy metals, nutrients, oil, pesticides, biocides, and other "pollutants." Since these pollutants are "attached" to fine particles, they are concentrated in the sediments, both suspended and deposited, in the upper reaches of the Bay and its tributary estuaries. Filter-feeding organisms which ingest these particles concentrate the contaminants. Butler (1966) has pointed out the ability of oysters to concentrate DDT in their pseudo feces, making it available in a more concentrated form to deposit feeders. Increases in the concentration of contaminants at each trophic level are well documented for radioactive elements and pesticides (Woodwell, 1967). This phenomenon has been referred to as "biological magnification."

Although there are few analyses of pesticides, herbicides, and heavy metals in Chesapeake Bay organisms, it might be anticipated that the concentrations of these constituents will be relatively high.

In summary, sediments are the estuary's natural archenemy and ultimate conqueror. As they fill in the basin they expel the intruding sea, converting the estuarine system back into a river valley system. At times, a man's activities have tended to both accelerate and decelerate this process, but their net effect has been to increase the overall sedimentation rate. The indirect effects of the sediments, particularly the fine-grained sediments that are accumulating in the Bay and its tributaries, are of greater significance to man than the long-term direct effects of filling. These indirect effects are poorly understood.

### Heavy Metals

The so-called heavy or trace metals (transition metals) are of considerable interest because certain of these metals are highly toxic to plants and animals, including man but are, of course, also essential for life. They are highly persistent and retain their toxicities for prolonged periods of time. Most heavy metals are concentrated in the bodies of organisms where they remain for prolonged periods of time and function as cumulative poisons. There are approximately 2 dozen metals which are highly toxic to plants and animals, but the most toxic, persistent, and abundant heavy metals in the marine environment include mercury (Hg), arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni). Since heavy metals are present in the earth's crust, they are carried both in solution and in suspension by rivers and streams into the Chesapeake Bay estuarine system and the rest of the marine environment. Man also contributes heavy metals to the Bay. Some heavy metals have been used extensively as pesticides and biocides and have been introduced into the environment from these sources.

There are very few data on the temporal and spatial distributions of any of the heavy metals in the Chesapeake Bay estuarine system or its tributary rivers. The most extensive studies have been made by J.H. Carpenter of The Johns Hopkins University's Chesapeake Bay Institute. He has kindly permitted me to summarize some of his unpublished results. Carpenter analyzed samples of Susquehanna River water collected at approximately weekly intervals from April 1965 through August 1966 at Lapidium, Maryland, located about 1 mile downstream from the dam at Conowingo. Using atomic absorption techniques, the samples were analyzed for the concentrations of iron, manganese, zinc, nickel, copper, cobalt, chromium, and cadmium in both the dissolved and suspended states. Carpenter distinguished between the solid material that was deposited by gravity settling after 10-14 days, and the solid material remaining in suspension after this settling period but which could be removed by filtration through membrane filters with an average pore size of $0.2\mu$. The heavy metals were extracted from the particulate matter in normal HCl at 60°C with constant agitation for 72 hours.

The river flow, the concentration of total suspended solids (suspended sediment) and the total concentrations of the several heavy metals were all highly variable during the period of observation, (figs. 21-23). The pattern of river flow shown in fig. 21 illustrates the characteristic seasonal variation of flow of the Susquehanna and other rivers in this region—high discharge in the spring followed by low to moderate flow throughout the summer and most of the fall. The obvious positive correlation between river flow and the concentration of suspended sediment illustrated in fig. 21 is well documented. The most striking thing about the heavy metal analyses is their marked variability. In general, high concentrations of the heavy metals were associated with high concentrations of suspended sediment, but there were some exceptions notably zinc, nickel, and cobalt during January, 1966.

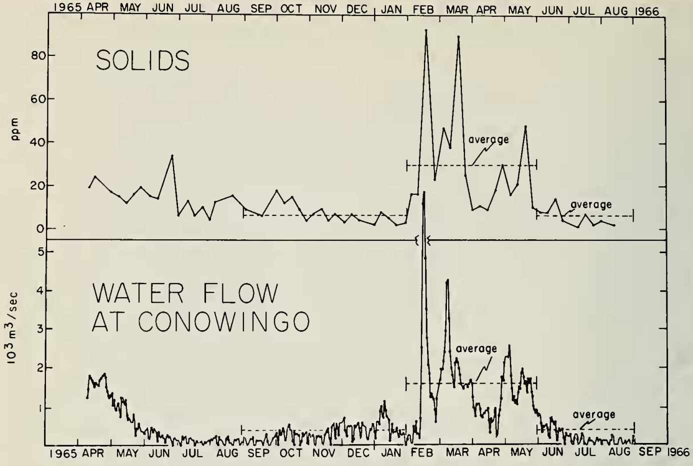


Fig. 21. Flow of the Susquehanna River and concentration of suspended sediment between April 1965 through August 1966 (J.H. Carpenter, personal communication).

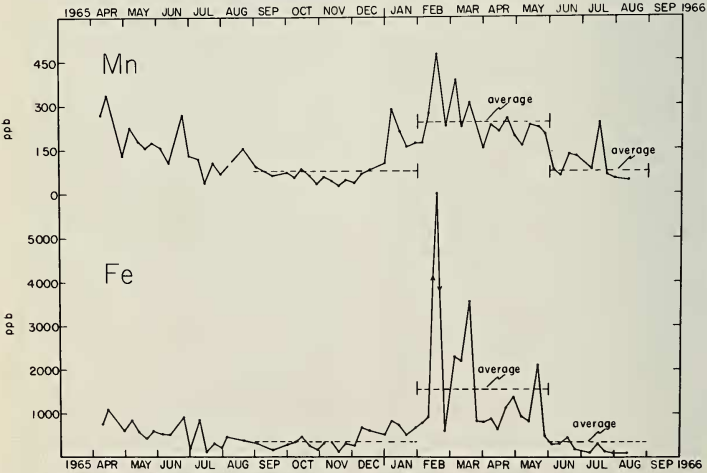


Fig. 22. Concentrations of total iron and manganese in Susquehanna River samples (J.H. Carpenter, personal communication).

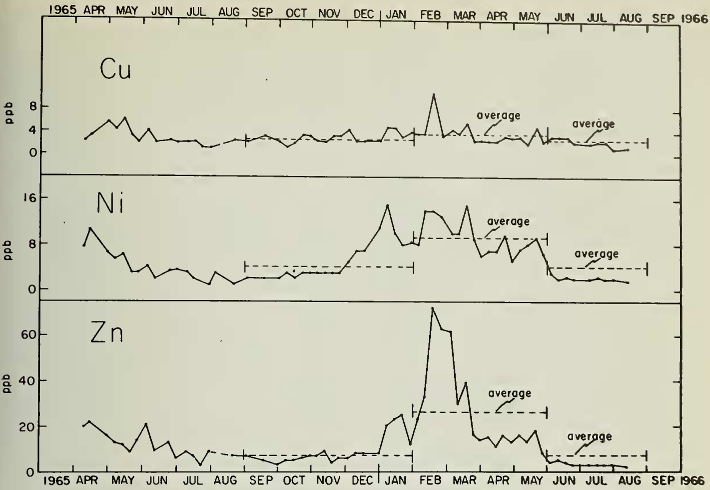


Fig. 23. Concentrations of total Cu, Ni, and Zn in Susquehanna River samples (J.H. Carpenter, personal communication)

The partitioning of iron, manganese, zinc, nickel and copper among the soluble, filtered solids and settled solids fractions showed marked seasonal variations. The occurrence of manganese in a soluble form, for example, appears to be seasonal with the necessary conditions being present during winter and early spring, (fig. 24). the seasonality of both the total concentration and the solubilization of many metals suggests the significance of organic matter and metals derived from decaying vegetation (Carpenter, personal communication). Vegetation in the drainage basin then appears to be a major source of heavy metal "pollution" to the Susquehanna and to the upper Chesapeake Bay.

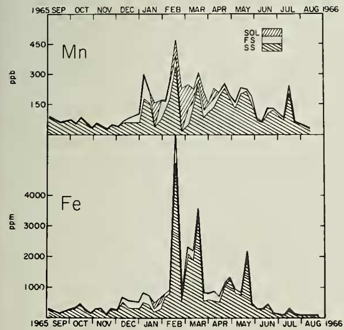


Fig. 24. Concentrations of iron and manganese in the soluble, filtered solids, and settled solids fractions of Susquehanna River samples (J.H. Carpenter, personal communication).

It is obvious from Carpenter's data that estimates of the inputs of the several metals must take into account the variability of the source. Estimates based on one sample (Turekian and Scott, 1967) or even on several samples are naive and are apt to be very misleading. Table 1 provides a comparison of estimates of the annual inputs of several heavy metals based on one sample (Turekian and Scott, 1967) with estimates based on weekly samples (Carpenter, 1971, personal communication).

For each of the 3 heavy metals for which there were common analyses, Turekian and

Table 1.—Heavy Metal Input to Chesapeake Bay From the Susquehanna River

| Constituent | Estimate Based on One Sample Collected in June of 1966[1] (tons/year) | Estimate Based on 52 Weekly Samples Collected during 1965-1966[2] |
|---|---|---|
| Manganese | 120,000 | 5,300 |
| Nickel | 3,000 | 215 |
| Cobalt | 1,500 | 88 |

Scott (1967) estimated annual discharges were more than an order of magnitude higher than Carpenter's. (Turekian and Scott 1967) attributed the high concentrations of heavy metals to industrial contamination and suggested that the inputs were sufficiently large to be of possible economic interest.

The Susquehanna River, supplying more than 90% of the total freshwater input to the Bay north of the Potomac, is the major source of freshwater and fluvial sediment to the upper Chesapeake Bay. Tidal currents provide most of the energy for the mixing of the fresh river water with the salty estuary water. There are very few reliable data on the spatial distributions of heavy metals in the waters of the Bay itself, and data on temporal distributions are not available. To assess man's affect on the distributions of heavy metal one must examine the only historical record that exists—the sedimentary record. Unfortunately, that record has received only meager examination.

Sediment samples taken on a cross-section near the Chesapeake Bay Bridge at Annapolis show variations in the concentrations of both iron and zinc of more than an order of magnitude. The variations are associated with changes in the grain size of the sediments; the coarser-grained sediments are impoverished in heavy metals relative to the finer sediments. There are also local spatial variations associated with spoil deposits which are enriched in certain of the heavy metals.

There are a few data that *suggest* there is a longitudinal gradient of heavy metals in the fine sediments of the Bay. Concentrations of heavy metals tend to be higher near the head of the Bay than farther seaward in the estuary. This might have been anticipated, since the fine sediments in the upper Bay are derived primarily from the Piedmont, while the fine sediments in the middle and lower reaches of the Bay are probably derived primarily from the shore erosion of Coastal Plain sediments—sediments originally derived from the Piedmont and now impoverished in heavy metals relative to their source rocks. The differences in the sources of organic matter may also be important in producing this gradient. This is an important problem; one which deserves further study.

Analyses of the longer-term sedimentary record are even more scarce. Recently a 135-cm-long core was taken in the upper Bay off Howell Point. Since the sedimentation rate in the area is probably between 5 and 10 mm/yr, the core represents 135-270 years of sedimentary history. The core was analyzed for extractable[3] iron and zinc at the surface and at 20-cm increments to the bottom of the core. One might have anticipated that the concentrations of iron and zinc would decrease with depth, since man's impact has presumably increased with time. The results showed, however, that below the surficial layer the concentrations were nearly uniform with depth. The concentration of zinc was about 70 ppm (dry weight) and the concentration of iron about 20 ppt. The uniformity may be attributable in part to the homogenization of the sediment by burrowing organisms. The core may not have been long enough to pass through the sedimentary horizon corresponding to the initiation of

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[1] Data from Turekian & Scott (1967), who filtered their water sample through an 0.45 $\mu$ APD Millipore filter, ashed it, and analyzed the residue spectrographically. This procedure results in a determination of something close to the concentrations of the total particulate fraction of the various metals.

[2] Data from J.H. Carpenter, personal communication. Carpenter's methods result in determinations of the dissolved fraction and the "extractable" particulate fraction. The extractable part of the particulate fraction may be less than the total particulate fraction, but it is probably never less than 50% of it.

[3] Using techniques described previously.

mining in the Susquehanna drainage basin about 130 years ago. These scant data do not demonstrate, however, that man's activities have increased the levels of iron and zinc in the upper Bay off Howell Point. Furthermore, they do not violate the hypothesis that the concentrations of these heavy metals have always been *naturally* high at this location, and that man has not has a measurable effect on their concentrations.

It might be anticipated that the industrial enrichment of heavy metals in the sediments of the Maryland portion of the Bay would be most obivous in Baltimore Harbor. Samples of surface sediment from Baltimore Harbor show large variations in their concentrations of heavy metals. Local areas are enriched by more than an order of magnitude in certain of the heavy metals, such as Zn, Cu, and Cd, over contiguous areas where levels are approximately equal to those in the open Bay. Man has almost certainly increased the concentrations of heavy metals in Baltimore Harbor, but the magnitude of his impact is not clear. The pertinent data are being compiled for a report to the Submerged Lands Commission of the State of Maryland (J.H. Carpenter, personal communication).

In summary, because of their presistence, and their toxicity at high concentrations, heavy metals are potentially dangerous pollutants. Heavy metals are introduced into the Bay, in solution and adsorbed on fine particles, as a result of the natural processes of weathering and erosion. They are also introduced into the Bay as a direct and indirect result of man's activities. Man's use of heavy metals in pesticides, biocides, and industrial applications have tended to increase the inputs of heavy metals to the Bay, as have mining and agriculture in the drainage basin. Man's dam building activities have tended to decrease the inputs. Dams on the lower Susquehanna trap large amounts of sediment and heavy metals, thus preventing them from reaching the Bay. The extent of man's impact on the spatial and temporal distributions of heavy metals in the Chesapeake Bay estuarine system is obscure.

The spatial and temporal distributions of heavy metals should be determined in the water, in the bottom sediments, and in selected organisms. Filter-feeding and deposit-feeding organisms which ingest fine sedimentary particles may be exposed to diets with relatively high concentrations of adsorbed heavy metals. Like many other estuarine pollution problems, the problem of heavy metals is not amenable to facile solution. This is an important area of research–one which has received far too little attention. It will require extensive sampling programs to establish the inputs of heavy metals to the Bay and to delimit their routes, rates, and reservoirs within the estuary.

### Summary

This paper describes the prevailing physical and chemical conditions of Chesapeake Bay and attempts to assess man's impact on these conditions. The properties which are considered are temperature, salinity, dissolved oxygen, nutrients, sediment, and heavy metals. Other important items are pesticides, herbicides, and oil.

There are marked natural spatial and temporal variations of water temperature throughout the Bay. Superimposed upon these are the "excess" temperatures which result from the discharge of condenser cooling water from power plants. The inputs of heated discharges from present power plants and from those now under construction do not appear to pose a threat to the Bay. Man's power "requirements," however, are increasing at an alarming rate, and the Bay does have a limit on its capacity to receive waste heat.

There are marked natural temporal and spatial variations of salinity in the upper reaches of the Bay and its tributaries. Man has had little effect on the distribution of salinity in the Chesapeake Bay system. Flow regulation of the Susquehanna would decrease the fluctuations of salinity in the upper Bay and would have a serious effect on the flushing of a number of small tributary estuaries.

There are relatively large natural spatial and temporal variations in dissolved oxygen. Low levels of dissolved oxygen have always occurred in the deeper waters of the main body of the Bay during the summer months as a result of natural processes. But man's activities have certainly increased the frequency, extent, and duration of low oxygen zones in the upper reaches of a number of the tributaries.

Man has dramatically increased the inputs of nutrients to the Chesapeake Bay estuarine system. The effects of the increased nutrients are concentrated in the upper reaches of the tributaries and in the upper Chesapeake Bay. In the Maryland Portion of the Bay, nutrients are at undesirable levels in the upper Potomac, and in Back River, and are near the upper limit in the upper Bay, the Patuxent, and in many of the smaller tributaries. The discharge of improperly treated dewage and municipal wastes constitute the most serious immediate threat to the Chesapeake Bay estuarine system.

Sediments are the estuary's natural archenemy and ultimate conqueror. Man's activities have, at times, tended to both increase and decrease the natural sedimentation rates, but his net effect has been to increase the overall sedimentation rate. The indirect effects of the fine-grained sediments are of more immediate concern than the direct effects of the infilling of the basin. These are poorly understood.

There are marked variations of heavy metals in the water, and in the sediments of Chesapeake Bay. The sources of heavy metals, the routes and rates of transport, and the patterns and rates of accumulation in the sediments are very poorly known. This is an important area of research.

There is very little published data on the occurrence of pesticides and herbicides in the waters, sediments, or organisms of the Chesapeake Bay estuarine system. It might be predicted however, that the concentrations would be relatively high in some of the filter-feeding and deposit-feeding organisms.

There have been a number of oil spills in Chesapeake Bay, but all have been relatively minor. Oil from illegal pumping of bilges, oils and greases in municipal wastes, and oil from filling stations that are washed into storm drains and eventually into the Bay pose an increasing threat.

Most of the serious sources of pollution that threaten the Bay can be reduced to acceptable levels by existing technology if sufficient funding is provided, and if efforts are directed to the "real" problems.

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